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Impact analysis of gold–silver refining processes through life-cycle assessment

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ABSTRACT:

Gold and silver are extracted through the gold-silver couple production process or the gold-silver-lead-zinc-copper combined production process. This paper aims to analyse and compare the life-cycle assessment (LCA) of the gold and silver refining processes. Two production routes are considered in this study: gold and silver refining through the gold-silver couple production process and gold and silver refining which are produced from the gold-silver-lead-zinc-copper combined production process. SimaPro software version 8.5 is used for the life-cycle assessment using the International Life Cycle Reference Data (ILCD) method and the cumulative energy demand method (CED). The geographic region considered in the original dataset is based on Papua New Guinea and Sweden. The major impact categories from the ILCD methods are climate change, human toxicity (cancer and non-cancer effects), ecotoxicity, ionising radiation (human health and ecotoxicity), eutrophication (freshwater, marine, and terrestrial), land use, water use, and mineral resources depletion. The impact categories where the results are analysed and presented here from the CED method are renewables, fossil fuels (oil, coal, and gas), biomass, nuclear, and embodied energy. The analysis results indicate that between gold-silver couple production and gold silver combined metal production process, refining through the gold-silver couple production process have greater environmental impacts. Furthermore, gold refining effects are larger as compared to the silver refining process. Among the significant impact categories, the most crucial is human toxicity (cancer and non-cancer). Results from the cumulative energy demand method shows that fossil-fuel consumption is larger than all other sources of energy demand in the precious-metal refining process.

1. Introduction

Gold is a popular precious metal for jewellery or bullion coin making, which exists and is preserved in refined gold form by the government as a monetary reserve asset or by an individual (World Gold Council, 2014). Gold is an isometric mineral which occurs with hydrothermal veins deposited by ascending solutions (Lagat, 2013). On the other hand, silver is primarily used for industrial or decorative uses, for making jewellery or silverware (Zhao, 2014). Silver, in the metallic state, is commonly associated with gold, copper, lead, and zinc (Ayres and Peiró, 2013). The primary source of gold and silver is surface mining, which requires extensive blasting. Further processing starts with the milling operation and concentrating the ore through the beneficiation process. The last step is the metal refining process (ELaw, 2014).

The metal mining, extraction, beneficiation, and refining process have their impacts on sustainability. The material inputs and outputs associated with the production process impact uniquely to the environment. Gold mining may disrupt vegetation, plant growth, and may give rise to acid mine drainage. Gold rushes can also affect energy resources, can harm forestation, and increase soil erosion (Fashola et al., 2016). Carbon-dioxide emission from the water pumps in mining may cause air pollution. Dust emission is also inseparable from mining activities. Due to heavy-metal emissions like lead, arsenic, and mercury, gold mining is detrimental to the environment (Abdul-Wahab and Marikar, 2012; Tchounwou et al., 2012). It is also worth mentioning that mining activities and transportation are responsible for causing air pollution. Transportation of the hydrocarbons to the gold mine is responsible for air pollution and so also is the dust fallout (Geiger et al., 2010). A particular type of refining operation also may change sulfuric acid towards the environment which contaminates water (Agency for

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Toxic Substances and Disease Registry, 1998). Refining operations may also produce gas bleed streams which contain highly toxic substances harmful for air pollution (Ragothaman and Anderson, 2017). Silver thiosulfate complexes get released to the environment which causes water pollution (Ledrich et al., 2005). In the form of silver sulphide, silver sulphate, silver carbonate, silver halides, and metallic silver; silver gets mixed with the environment (Purcell and Peters, 1998).

To ensure the sustainability of metal mining and their key processes, it is evident that the environmental impacts associated with the metal production or mining process should be assessed thoroughly (Mahmud et al., 2018, 2019). Until now few studies have been published on life cycle assessment of metal-refining processes. These literature works were mostly considering the entire mining process as a unit process where the refining process is also embedded. Some of the studies are summarised in Table 1. Previous studies considered that renewable energy integration resources would be beneficial for sustainability. There are a few studies which summarize the solar industrial process heating systems over different industrial processes (Farjana et al 2018e, 2018f).

In this paper, the life cycle environmental impacts of the precious metal (gold and silver) refining process is assessed and reported in detail. The paper starts with a brief introduction followed by a detailed overview of gold and silver refining processes in Section 2. Section 3 discusses the world producers and their production summary of gold and silver. Section 4 illustrates life-cycle assessment assumptions and methodologies for analysis. Section 5 presents the environmental impacts, compares them and discusses the overall results of impact analysis, and makes recommendations to make the metal-refining process more sustainable and environment-friendly in future. Finally, Section 6 gives the concluding remarks.

2. Precious metal refining

The metal refining process used for gold and silver depends on the composition of the materials in the feed. The process used to separate silver from gold is known as “parting” (Nriagu, 1994). This operation can be done either electronically or by acid leaching. In either case, silver is removed from the gold. To remove the impurities, further treatment is required (Fisher, 1987). In the couple production of gold and silver, they are also recovered from the base metal. From these operations, the refining slimes are used for precious metal recovery.

There are two basic processes of gold refining: The Miller Chlorination process in conjunction with Wohlwill electrolysis and the Minotaur process. The Miller Chlorination process is a pyrometallurgical process where partially refined gold is received from the mines; gold impurities can be separated by using chlorine gas (Feather et al., 1997). The chlorine gas does not react with gold, but it will combine with silver and other metals to chlorides (Homs et al., 2013). The Wohlwill process runs in conjunction with the Miller chlorination process to refine gold until almost 100% purity is achieved. The gold using the miller process is cast into another anode, which is then sent into an electrolytic plant (Fisher, 1987). This process is based on the principle of the solubility of gold and the insolubility of silver in an electrolytic solution of gold chloride in hydrochloric acid (Nicol et al., 1987). In the Minotaur process, the gold-bearing feed is leached in a chloride solution. The resultant material then undergoes solvent extraction to reject impurities, then is stripped to produce a concentrated gold solution. From this process, the high-purity gold powder is precipitated by reduction

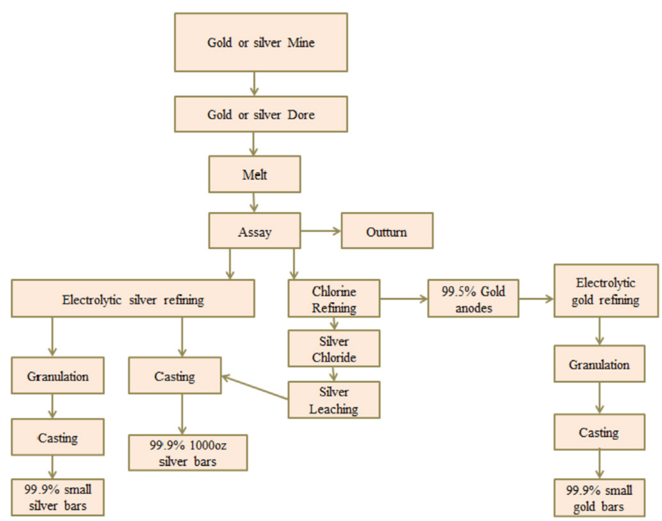

Fig. 1. Gold and silver refining process from gold or silver mines.

Table 1
Previous studies based on LCA of metal refining processes.

Metal	Reference	Major Impact categories from the refining process	Important findings
Ferronickel	Bartzas et al. (Bartzas and Komnitsas, 2015)	Global warming potential, acidification potential, primary energy demand (444 kWh/t ore)	25% of total acidification potential is from refining. Also impacts on global warming. Electricity consumption is high which increases carbon-dioxide emission. Sulphur-based burdens are also created from electricity demand in refining.
Gold, Silver	Haque et al. (Norgate and Haque, 2012)	Global warming, primary energy demand (chlorination 480 kWh/t ore, electrolytic process 325 KWh/t ore)	The contributions of gold and silver refining are very small as compared with other stages of mining. In comparison with other metals, the contribution is also very small.
Copper	Norgate (Norgate, 2001; Norgate and Rankin, 2000)	Global warming, primary energy demand (electrorefining 323 kWh/t Cu)	The metal production and the refining stage make the greatest contribution to the overall process, 61% of the total energy consumption.
	Northey et al. (Northey et al., 2013)	Energy requirements (285–390 kWh/t Cu)	Energy requirement is dependent on the composition of concentrate, but not on the original ore grade.
Aluminium	Nunez et al. (Farjana et al., 2019a; Nunez and Jones, 2016)	Global warming, 13% of thermal energy production for the global scenario of aluminium inventory, 15% of thermal energy requirements for global minus China generated from alumina refining.	Largest greenhouse-gas contributions were attributed to the alumina refining and electrolysis stage, with electricity and thermal energy being the major contributing factors.
Zinc	Qi et al. (Qi et al., 2017)	Human toxicity, energy demand (7.81 MJ/kg for zinc-ore mining and refining)	Refining through the hydrometallurgical process was considered, which generates zinc, mercury, and lead. These have impacts like human toxicity.
Ferromanganese	Westfall et al. (Westfall et al., 2016)		Refining is considered which reduces the carbon content of alloy, requires upstream electricity, oxygen, gases.

(Feather et al., 1997). Fig. 1 shows the process flow chart of the gold-silver refining process, which illustrates the major processes involved in gold-silver refining; many sub-processes are ignored to simplify it.

Gold or silver mines use ore-processing technologies using various techniques with an alloy composed of gold-silver which is known as Dore bar (Bausero et al., 2004). There should be no pockets of high purity or low purity within the Dore bar. The sample taken from the Dore bar is assayed to determine the exact amount of gold or silver. The Dore bar then undergoes a chlorine refining process known as “Miller process”. The Miller process involves bubbling chlorine gas through the Dore bar to dissolve the contained silver to form silver chloride, which accumulates as slag at the top (Grayson, 2007). This process produces 99.5% pure gold. The silver chloride then goes through a silver leaching process where base metals are removed. The silver leaching process produces metallic silver, which then they pass through electrolysis. The electrolysis process helps to complete the rest of the refining process (Bard and Sobral, 2008). When there is a market demand for high purity gold, then the 99.5% pure gold bars produced from the chlorine refining process are cast into anodes for electrolytic refining, which is defined as the “Wohlwill process”. In a bath of hydrochloric acid, the anodes are placed, and pass faces electric currents to dissolve the gold. After dissolving, the gold gets deposited into a cathode with 99.9% purity. However, in producing high-purity silver bars, silver anodes are dissolved in a nitric-acid bath. This nitric-acid bath then melts the cathodes, granulates the silver metal which is cast into 99.9% pure silver bars (Nriagu, 1994).

3. Materials and methods

Life-cycle assessment is an environmental-impact analysis tool based on the International Organization for Standardization- ISO 14040, which aims to quantify the impacts on human health, ecosystem, and resources based on standard impact-assessment methodologies (Farjana et al., 2019a; S.H. Farjana et al., 2018a,b,c,d). There are four major steps which should be completed for a successful LCA analysis: goal and scope definition, life-cycle inventory containing material inputs and outputs, life-cycle assessment based on standard methodologies, and the overall interpretation of the results (Shahjadi Hisan Farjana et al., 2018a,b,c,d). In this paper, the goal is to analyse the environmental impacts caused by the different processing routes of gold and silver refining. The difference between these processes is their co-production of different metals (Farjana et al., 2019b). The scope of this work contains the environmental impacts and emissions on major impact categories of human health, ecosystem, and resources. The system boundary is a cradle-to-gate assessment of the gold and silver refining processes. The life-cycle inventory datasets contain the quantified values of raw materials, products, fuels, energies, tailings, outputs emissions to air and water, and the final product (Farjana et al., 2019c). Fig. 2 shows the system boundary followed in this study.

Table 2 describes the life-cycle inventory datasets considered in this study collected from previous literature and databases. The functional unit chosen is 1 kg of each product (gold, silver) and the comparative results are discussed. The geographical coverage chosen here is for Papua New Guinea and Sweden. The inventory datasets for gold and silver couple production is based on plants in Papua New Guinea. The inventory datasets for gold-silver combined production with a few other metals are based on datasets from Sweden. The analysis methods used here are the International Life Cycle Reference Data System (ILCD) for assessing the midpoint indicator-based impact categories, the IMPACT 2002 + method for endpoint indicator-based impact categories, and the Cumulative Energy demand method (CED) to assess and quantify the fuel consumption by energy type in each step or material involved in the production process (Lehtinen et al., 2011). SimaPro software version 8.5 is used for conducting a life-cycle assessment (PRé, 2018). As gold and silver never come to production alone, the allocation method must be applied. The revenue-based allocation method is employed here for quantifying the impacts caused by the gold and silver refining processes. When considering the gold-silver refining which comes with other metals like lead, zinc, copper, the refining of these metals is not considered here. According to the standard practices in life-cycle assessment techniques in the metal-mining industries, coproduct allocation must be avoided whenever possible. It is considered that any metals other than gold and silver are not going outside the system (Nuss and Eckelman, 2014; Raugei and Ulgiati, 2009; Weidema and Norris, 2002). For

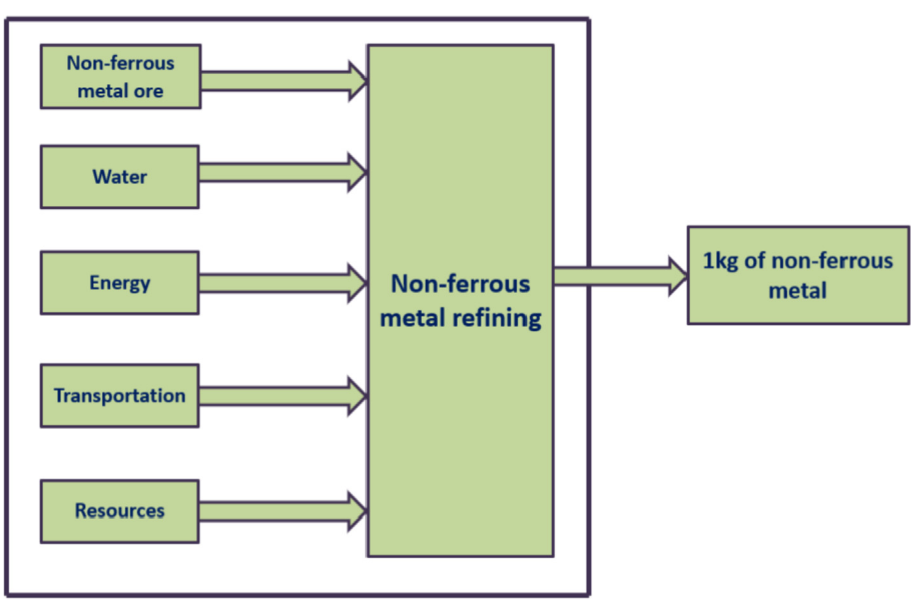

Fig. 2. Gold and silver refining process system boundary.

Table 2
Life-cycle inventory inputs and outputs for refining processes under consideration.

Life-cycle inventory inputs and outputs	Gold refining from couple production	Gold refining from combined production	Silver refining from couple production	Silver refining from combined production	Unit
Metal produced	1	1	1	1	kg
Gold or silver	1.11	1	1.11		kg
Water, ocean	0.09		28.5		m^3
Water, well	1.18E03			1.6E-03	m^3
Water, unspecified	136.65		3.3		m^3
Diesel, burned in diesel-electric generating set	1.17E03		28.24		MJ
Diesel	1.52E05		3.67E03		MJ
Transport, van <3.5 t	6.25		0.15		tkm
Heavy fuel oil	4.08E04	108.35	987	1.86	MJ
Natural gas	2.2E5	0.66	5.32E03	0.01	MJ
Acetylene	0.115		2.7E-03		kg
Sodium cyanide	123.19		2.98		kg
Limestone	1.22E03		29.44		kg
Sodium hydroxide, 50% in H_2O	11.37		0.27		kg
Chemicals organic	29.05		0.7		kg
Charcoal	32.66		0.78		kg
Zinc	2.83		0.07		kg
Sulfuric acid	3.62		0.09		kg
Hydrochloric acid	12.73		0.31		kg
Steel	281.36		6.79		kg
Blasting	206.75		4.99		kg
Transport, lorry >16 t	1.15E03	397.45	27.86	6.81	tkm
Mine, gold and silver	8.28E-07		2E-08		p
Facilities precious metal refinery	3.24E-07	1.14E-06	7.83E-09	1.96E-08	p
Electricity		193.86		3.33	kWh
Hard coal		4.5E04		770.99	MJ
Oxygen, liquid		1.42E03		24.26	kg
Facilities anode refinery		4.05E-07		6.94E-09	p
Transport, freight		397.451		6.81	tkm
Emissions to air					
Copper	3.7E-04	0.02	9.05E-06	2.9E-04	kg
Lead	1.2E-04	0.42	2.9E-06	7.2E-03	kg
Zinc	1.03E-04	0.06	2.5E-06	1.09E-03	kg
Carbon dioxide, fossil	33.08		0.798		kg
Selenium		1.9E-03		3.3E-05	kg
Cadmium		8.7E-04		1.4E-05	kg
Arsenic		2.8E-03		4.92E-05	kg
Mercury		1.6E-03		2.78E-05	kg
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p		2.75E-08		4.71E-10	kg
Heat, waste		2.7E04		464.41	MJ
Particulates, < 2.5 um		6.3E-03		1.08E-04	kg
Particulates, > 2.5 μm, and <10 μm		7.7E-04		1.33E-05	kg
Particulates, > 10 um		6.1E-04		1.06E-05	kg
Emissions to water					
Arsenic, ion	9.9E-04		2.4E-05	2.5E-04	kg
Cadmium, ion	3.9E-03		9.5E-05		kg
Copper, ion	4.04	5.8E-03	0.097	1E-06	kg
Cyanide	7.04		0.17		kg
Lead	0.01	6.3E-03	2.8E-04	1.09E-04	kg
Nickel, ion	0.03		6.6E-04		kg
Zinc, ion	0.26	0.03	6.3E-03	5.1E-04	kg
Arsenic, ion	0.02	0.014	4.8E-04		kg
Cadmium, ion	0.09	7.4E-04	2E-03	1.28E-05	kg
Copper, ion	1.46		0.04		kg
Cyanide	1.89		0.05		kg
Lead	2.8E-03		6.7E-05		kg
Mercury	2E-04	1.7E-03	5.4E-06	3E-05	kg
Nickel, ion	1.28	2.3E-03	0.03	4.06E-05	kg
Zinc, ion	34.83		0.84		kg
Waste to treatment					
Disposal, sulfidic tailings	3.3E05	3.17	8.05E03	0.05	kg
Disposal, municipal solid waste		2.62		0.04	kg
Disposal, wood untreated		5.93		0.1	kg
Disposal, paper		0.09		1.4E-03	kg
Disposal, packaging cardboard		0.55		9.4E_03	kg
Disposal, refinery sludge		2.81		0.05	kg

further details about the allocation technique, the SimaPro manual should be consulted (Goedkoop et al., 2014).

4. Results

4.1. LCA results of gold refining produced from couple production of gold-silver

Table 3 shows the characterised results of the life-cycle assessment of gold refining from couple production of gold and silver. Fig. 3 shows the normalised results based on the midpoint indicator-based impact categories. Fig. 4 shows the single-scored results from the ILCD method, which identifies the significant contributions of the inputs materials or processes in the gold refining. According to the analysis results presented here in Table 3, Figs. 3 and 4, it is evident that gold refining from couple production of gold and silver impacts largely on human toxicity cancer effects, freshwater eutrophication, climate change, terrestrial eutrophication, and photochemical ozone formation. After analysing the material inventory, it has been found that steel use in gold refining process from couple production affects largely on human toxicity cancer effects. Diesel burned in building machines also affects ecosystems and climate change. From the other inventory materials, the blasting process and the sulphide tailing disposal affects the environment.

4.2. LCA results of gold refining produced from combined production of five metals

Table 4 shows the characterised results of the life-cycle assessment of gold refining from the combined production of gold, silver, lead, zinc, and copper. Fig. 5 shows the normalised results based on the midpoint indicator-based impact categories. Fig. 6 shows the single-scored results from the ILCD method, which identifies the significant contributions of the inputs, materials or processes in gold refining. According to the analysis results presented here in Table 4, Figs. 5 and 6, it is evident that gold refining from the combined production of gold and other four metals impacts largely on human toxicity non-cancer effects, ionising radiation- HH, terrestrial eutrophication, acidification, and photochemical ozone formation. After analysing the material inventory, it is found that the impacts due to gold metal produced from the gold beneficiation

Table 3
LCA results for gold refining produced from couple production of gold-silver.

Impact category	Unit	Total	Diesel	Natural gas	Steel, converter, chromium steel
CC (Climate change)	kg CO_2 eq.	3.3E04	1.3E04	1.3E04	1.2E03
OD (Ozone depletion)	kg CFC-11 eq.	2E-03	1.6E-03	1.37E-06	1.65E-05
HTNC (Human toxicity, non-cancer effects)	**CTUh**	**1E-03**	**1.2E-04**	**9.08E-06**	**5E-04**
HTC (Human toxicity, cancer effects)	CTUh	6E-04	1.96E-06	7.86E-07	5.65E-04
PM (Particulate matter)	kg PM2.5 eq.	28.55	17.34	0.23	1.58
IRHH (Ionizing radiation HH)	kBq U235 eq.	47.15	0.27	2.2E-04	46.7
IRE (Ionizing radiation E)	CTUe	4.2E-04	2.32E-07	2.08E-10	4.2E-04
POF (Photochemical ozone formation)	kg NMVOC eq.	295.84	187.81	7.24	3.77
AP (Acidification)	molc H+ eq.	280.98	144.18	4.46	7.09
TE (Terrestrial eutrophication)	molc N eq.	1.24E03	692.78	24.49	13.73
FEU (Freshwater eutrophication)	kg P eq.	65.45	2.7E-03	2.6E-04	5.7E-04
ME (Marine eutrophication)	kg N eq.	100.14	63.2	2.24	1.22
FET (Freshwater ecotoxicity)	CTUe	1.3E04	670.15	8.97	6.4E3
LU (Land use)	kg C deficit	1.6E04	5.64	−7.45	315.36
WRD (Water resource depletion)	m^3 water eq.	225.67	4.39	0.09	1.85
MFRRD (Mineral, fossil & ren resource depletion)	kg Sb eq.	1.02E-10	4.98E-11	4.46E-14	3.51E-12

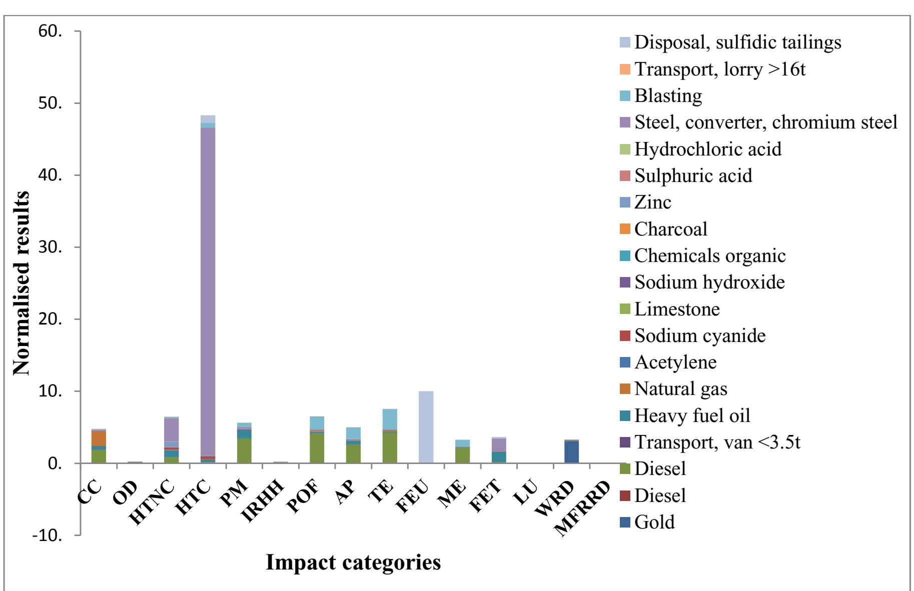

Fig. 3. LCA results for gold refining produced from couple production of gold-silver (normalised results).

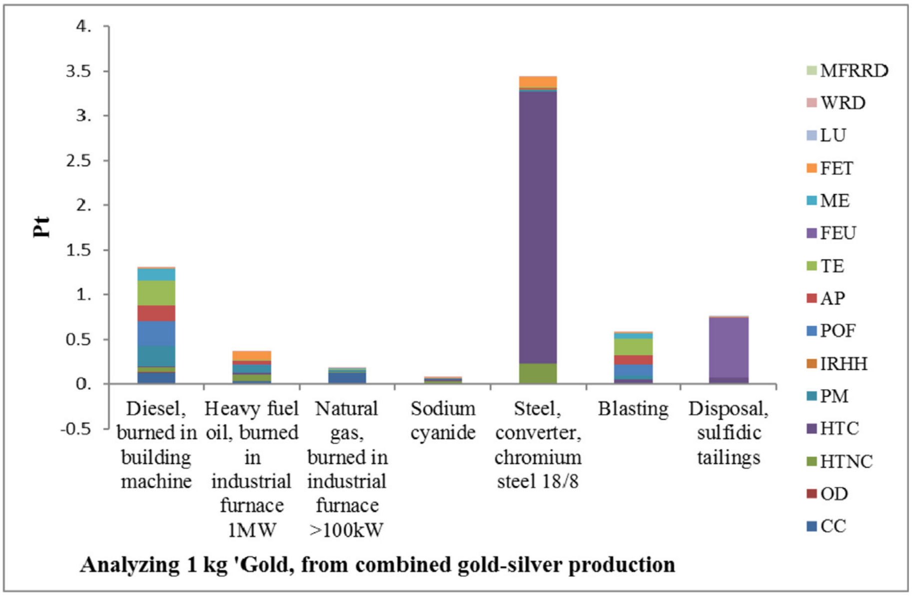

Fig. 4. LCA results for gold refining produced from couple production of gold-silver (single scored results).

Table 4
LCA results for gold refining produced from the combined production of gold-silver-lead-zinc-copper.

Impact category	Unit	Total	Gold, from combined metal production, at the refinery	Gold, from combined metal production, at beneficiation	Hard coal, burned in industrial furnace 1–10 MW
CC (Climate change)	kg CO_2 eq.	9.4E03	0	3.64E03	4.6E03
OD (Ozone depletion)	kg CFC-11 eq.	2.5E-04	0	2.25E-04	1.25E-05
HTNC (Human toxicity, non-cancer effects)	**CTUh**	**7.1E-03**	**6.5E-03**	**3.88E-04**	**1.7E-04**
HTC (Human toxicity, cancer effects)	CTUh	6.05E-05	2.51E-05	2.37E-05	1.11E-05
PM (Particulate matter)	kg PM2.5 eq.	15.61	2E-03	10.69	4.7
IRHH (Ionizing radiation HH)	kBq U235 eq.	2.18E03	0	2.1E03	0.62
IRE (Ionizing radiation E)	CTUe	0.019	0	0.02	2.19E-09
POF (Photochemical ozone formation)	kg NMVOC eq	189.19	0	172.22	13.5
AP (Acidification)	molc H+ eq.	233.2	0	191.71	38.88
TE (Terrestrial eutrophication)	molc N eq.	1.01E3	0	951.06	46.95
FEU (Freshwater eutrophication)	kg P eq.	2.85	0	2.84	2.4E-04
ME (Marine eutrophication)	kg N eq.	64.81	0	59.26	4.28
FET (Freshwater ecotoxicity)	CTUe	3.1E03	1.63E03	1193.14	288.84
LU (Land use)	kg C deficit	3.6E03	0	3335.39	309.14
WRD (Water resource depletion)	m^3 water eq.	21.19	0	19.88	0.158
MFRRD (Mineral, fossil & ren resource depletion)	kg Sb eq.	6.82E-11	0	6.69E-11	5.05E-13

process which is used in the gold refining process from couple production affect human toxicity, non-cancer effects, eutrophication, acidification, and ozone formation.

4.3. LCA results of silver refining produced from couple production of gold-silver

Table 5 shows the characterised results of the life-cycle assessment of silver refining from couple production of gold and silver. Fig. 7 shows the normalised results based on the midpoint indicator-based impact categories. Fig. 8 shows the single-scored results from the ILCD method, which identifies the significant contributions of the inputs materials or processes in the gold refining. According to the analysis results presented here in Table 5, Figs. 7 and 8, it is evident that silver refining from the couple production of gold and silver impacts largely on human toxicity cancer effects, freshwater eutrophication, climate change, terrestrial eutrophication, and photochemical ozone formation. After analysing the material inventory, it has been found that steel used in silver refining process from the couple production affects human

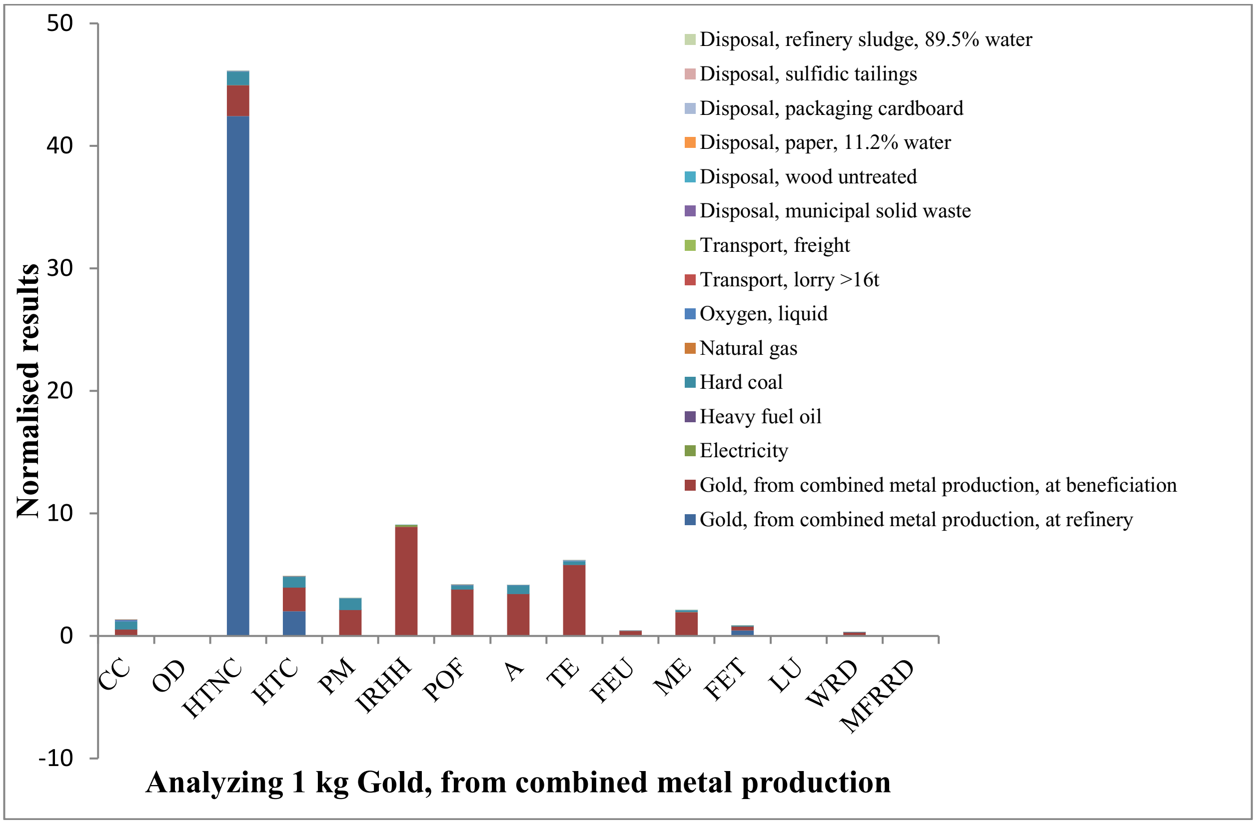

Fig. 5. LCA results for gold refining produced from the combined production of gold-silver-lead-zinc-copper (normalised results).

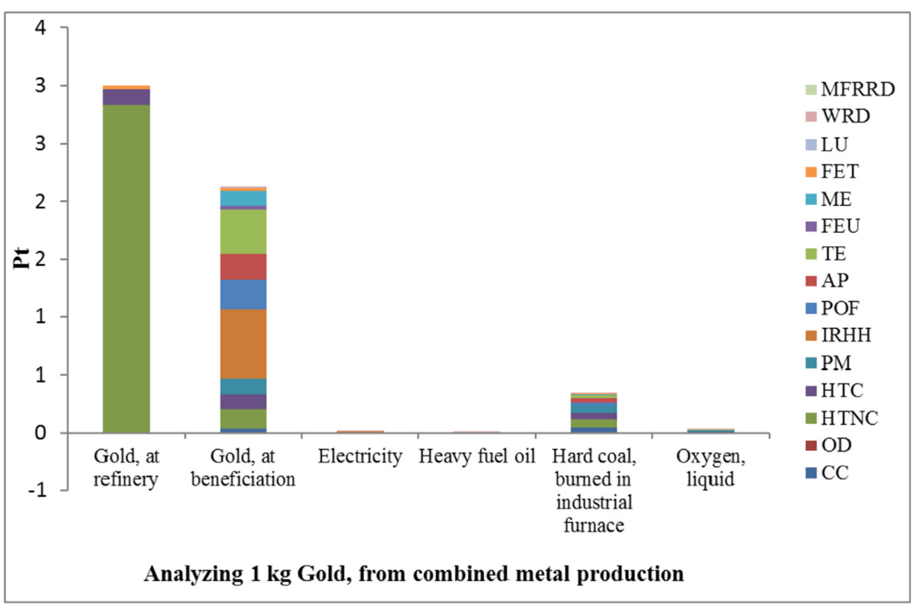

Fig. 6. LCA results for gold refining produced from combined production of gold-silver-lead-zinc-copper (single scored results).

toxicity, cancer effects. Diesel burned in building machines also affects ecosystems and climate change. From the other inventory materials, the blasting process and the sulphide tailing disposal affects the environment. These results are like the major impact categories and responsible materials found from the gold refining process from couple production. However, the effects are lower from silver refining rather than for gold refining. This must be due to the allocation technique because gold is more costly than silver, which imparts more impacts from gold refining. However, the consumption of materials for gold refining is also larger than for silver refining processes, which in turn results in the more sustainable silver refining process.

Table 5
LCA results for silver refining produced from couple production of gold-silver.

Impact category	Unit	Total	Diesel burned in building machine	Natural gas	Steel, converter, chromium steel
CC (Climate change)	kg CO_2 eq.	815.44	319.81	333.79	29.69
OD (Ozone depletion)	kg CFC-11 eq.	5.31E-05	4.02E-05	3.3E-08	3.98E-07
HTNC (Human toxicity, non-cancer effects)	CTUh	2.42E-05	2.98E-06	2.19E-07	1.21E-05
HTC (Human toxicity, cancer effects)	CTUh	1.45E-05	4.74E-08	1.9E-08	1.36E-05
PM (Particulate matter)	kg PM2.5 eq.	0.69	0.42	5E-03	0.04
IRHH (Ionizing radiation HH)	kBq U235 eq.	1.14	6.4E-03	5.53E-06	1.13
IRE (Ionizing radiation E)	CTUe	1.02E-05	5.61E-09	5.02E-12	1.02E-05
POF (Photochemical ozone formation)	kg NMVOC eq.	7.14	4.54	0.17	0.09
AP (Acidification)	molc H+ eq.	6.78	3.48	0.11	0.17
TE (Terrestrial eutrophication)	molc N eq.	29.95	16.73	0.59	0.33
FEU (Freshwater eutrophication)	kg P eq.	1.58	6.62E-05	6.44E-06	1.38E-05
ME (Marine eutrophication)	kg N eq.	2.42	1.53	0.05	0.03
FET (Freshwater ecotoxicity)	CTUe	330.61	16.18	0.22	155.34
LU (Land use)	kg C deficit	389.39	0.14	−0.18	7.62
WRD (Water resource depletion)	m^3 water eq.	5.45	0.11	2.1E-03	0.04
MFRRD (Mineral, fossil & ren resource depletion)	kg Sb eq.	2.45E-12	1.2E-12	1.08E-15	8.48E-14

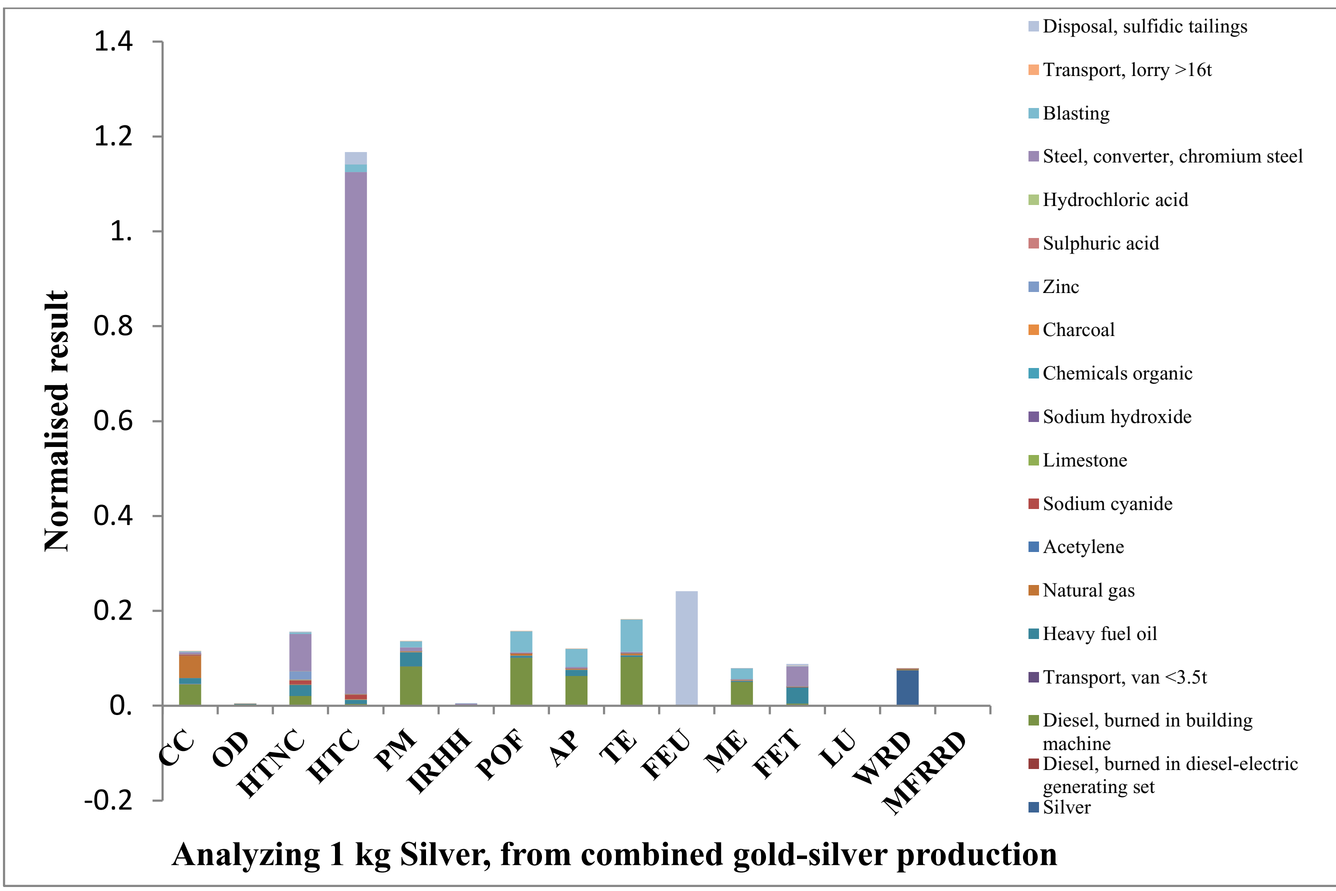

Fig. 7. LCA results for silver refining produced from couple production of gold-silver (normalised results).

4.4. *LCA results of silver refining produced from combined production of five metals*

Table 6 shows the characterised results of the life-cycle assessment of silver refining from the combined production of gold, silver, lead, zinc, and copper. Fig. 9 shows the normalised results based on the midpoint indicator-based impact categories. Fig. 10 shows the single-scored results from the ILCD method, which identifies the significant contributions of the inputs materials or processes in gold refining. According to the analysis results presented here in Table 6, Figs. 9 and 10, it is evident that silver refining from the combined production of gold and the other four metals impacts largely on human-toxicity non-cancer effects, ionising radiation (HH), terrestrial eutrophication, acidification, and photochemical ozone formation. After analysing the material inventory, it is found that impacts due to silver metal produced from the silver beneficiation process in use for the further refining process from the couple production affect human toxicity, non-cancer effects, eutrophication, acidification, and ozone formation. These results are like the major impact categories and responsible materials found from the gold refining process from combined production, but the effects are lower from silver refining than for gold refining.

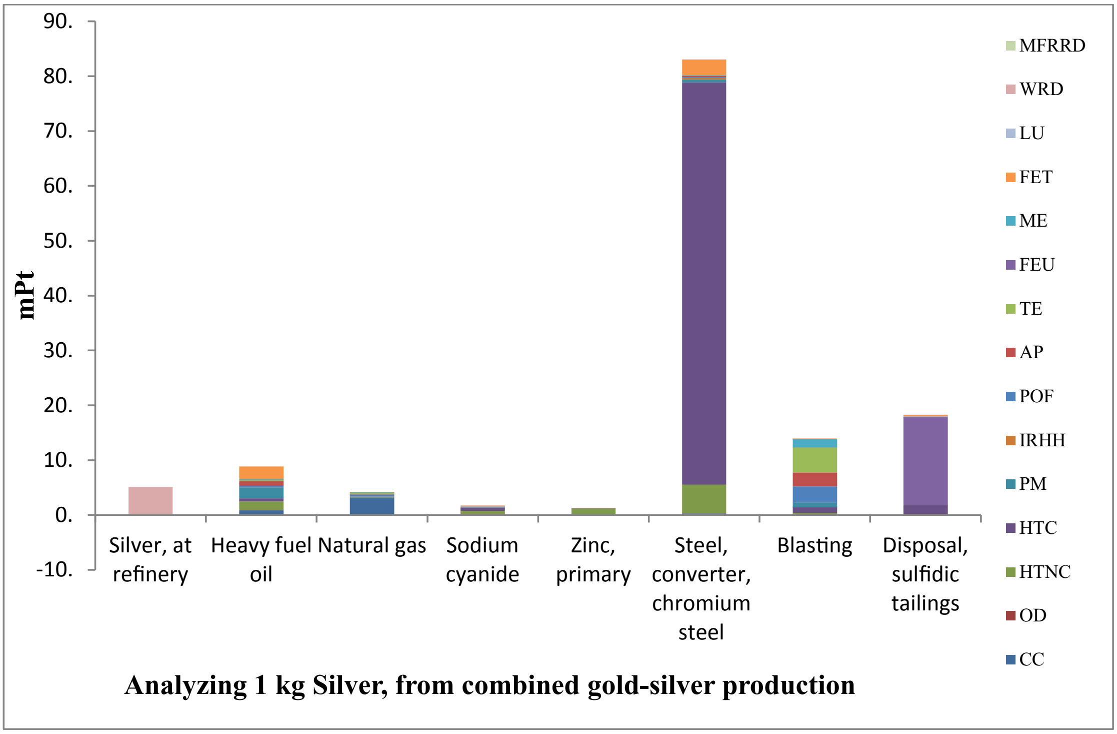

Fig. 8. LCA results for silver refining produced from couple production of gold-silver (single scored results).

Table 6
LCA results for silver refining produced from the combined production of gold-silver-lead-zinc-copper.

Impact category	Unit	Total	Silver, at the refinery	Silver, at beneficiation	Hard coal
CC (Climate change)	kg CO_2 eq.	161.19	0	62.12	78.57
OD (Ozone depletion)	kg CFC-11 eq.	4.26E-06	0	3.84E-06	2.14E-07
HTNC (Human toxicity, non-cancer effects)	CTUh	1.2E-04	1.13E-04	6.59E-06	2.92E-06
HTC (Human toxicity, cancer effects)	CTUh	1.03E-06	4.3E-07	4.05E-07	1.9E-07
PM (Particulate matter)	kg PM2.5 eq.	0.266	3.8E-05	0.18	0.08
IRHH (Ionizing radiation HH)	kBq U235 eq.	37.34	0	36.69	0.01
IRE (Ionizing radiation E)	CTUe	3.37E-04	0	3.31E-04	3.75E-11
POF (Photochemical ozone formation)	kg NMVOC eq.	3.23	0	2.94	0.23
AP (Acidification)	molc H+ eq.	3.98	0	3.27	0.67
TE (Terrestrial eutrophication)	molc N eq.	17.28	0	16.24	0.8
FEU (Freshwater eutrophication)	kg P eq.	0.05	0	0.05	4.09E-06
ME (Marine eutrophication)	kg N eq.	1.11	0	1.01	0.07
FET (Freshwater ecotoxicity)	CTUe	54.03	28.04	20.34	4.95
LU (Land use)	kg C deficit	62.06	0	56.54	5.29
WRD (Water resource depletion)	m^3 water eq.	0.36	0	0.34	3E-03
MFRRD (Mineral, fossil & ren resource depletion)	kg Sb eq.	1.17E-12	0	1.14E-12	8.64E-15

This must be due to the allocation technique because gold is more costly than silver, which imparts more impacts from gold refining. However, the consumption of materials for gold refining is also larger than for silver refining, which in turn results in a more sustainable silver refining process.

5. Discussion

5.1. Comparative analysis using the ILCD method

Table 7, Fig. 11, and Fig. 12 describe the comparative life-cycle assessment from gold or silver refining processes produced either from the couple production of gold and silver or the combined production of five non-ferrous metals. Table 7 shows the characterised results. Fig. 11 shows the normalised results while Fig. 12 shows the single scored results. The analysis results using the ILCD method reveal that the gold and silver refining processes from the couple production have a greater effect than the refining process using combined production. The major impacts categories include human-toxicity cancer effects, acidification, eutrophication, ecotoxicities, land use, water use, and mineral resources depletion. On the other hand, the gold and silver refining from the combined production of five metals impacts largely on human toxicity (non-cancer effects), ionising radiation (both human health and ecosystems).

5.2. Comparative LCA using the IMPACT 2002 + method

Table 8 and Fig. 13 present the endpoint indicator-based results using the IMPACT 2002 + method for the gold and silver refining processes from the couple production of gold-silver and combined production of five metals. The analysis results compare the effects

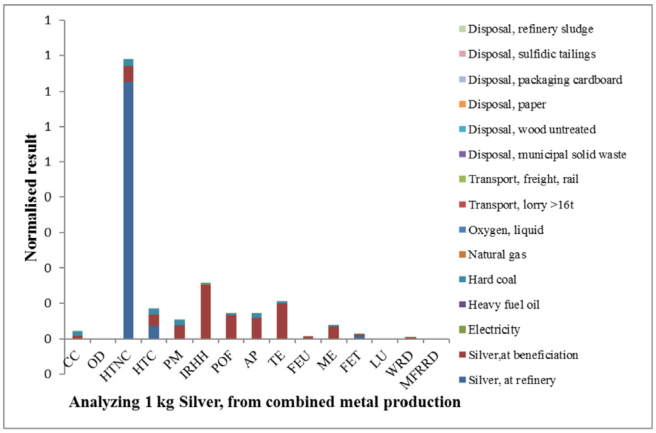

Fig. 9. LCA results for silver refining produced from the combined production of gold-silver-lead-zinc-copper (normalised results).

on human health, ecosystem, climate change, and resources. In comparison among these four categories, the human-health impacts are greatest from the gold-silver refining processes. Impacts on ecosystems and climate change are also larger, while impacts on resources are negligible. In comparison between the two types of refining process considered here, gold produced from the couple production more than gold produced from combined production in the cases of human health and climate change. On the other hand, gold produced from the combined production affects ecosystems more than the other type of refining process.

5.3. Comparative analysis using CED method

Table 9 and Fig. 14 shows comparative results among the metal refining processes based on their energy consumption for each type of fuel in use. Table 9 shows the characterised results while Fig. 14 shows the final weighted results. According to the analysis results presented here, gold produced from the couple production refining process consumes the largest amount of fossil fuels (oil and gas) and embodied energy. Gold refining from the combined production consumes a greater amount of renewable energy, coal, biomass, and nuclear energy. It is also evident that, between these energy sources, oil and gas consumption in the gold refining processes from the couple production is greatest.

5.4. Sensitivity analysis based on the technology mix

Table 10 illustrates a detailed sensitivity analysis that has been carried out based on the alloying properties of the steel consumed in the gold-silver refining processes produced from the couple production of gold and silver. There are three case scenarios for each metal (gold or silver).

Case study 1- the base-case scenario which uses chromium steel 18/8.
Case study 2- the tentative case if low-alloyed steel replaces the chromium steel 18/8.
Case study 3- the tentative case if unalloyed steel replaces the chromium steel 18/8.

According to the results presented in Table 10, using low-alloyed steel or unalloyed steel does not affect reducing climate change, land use, acidification, and freshwater eutrophication. Little effort is justifiable in reducing the environmental impacts caused in particulate matter, photochemical ozone formation, eutrophication, and resources depletion. However, impacts can be reduced to a great extent in human toxicity (cancer and non-cancer effects), and ionising radiation (human health and ecosystems). On the other hand, employment of low-alloyed or unalloyed steel will be detrimental for freshwater ecosystems.

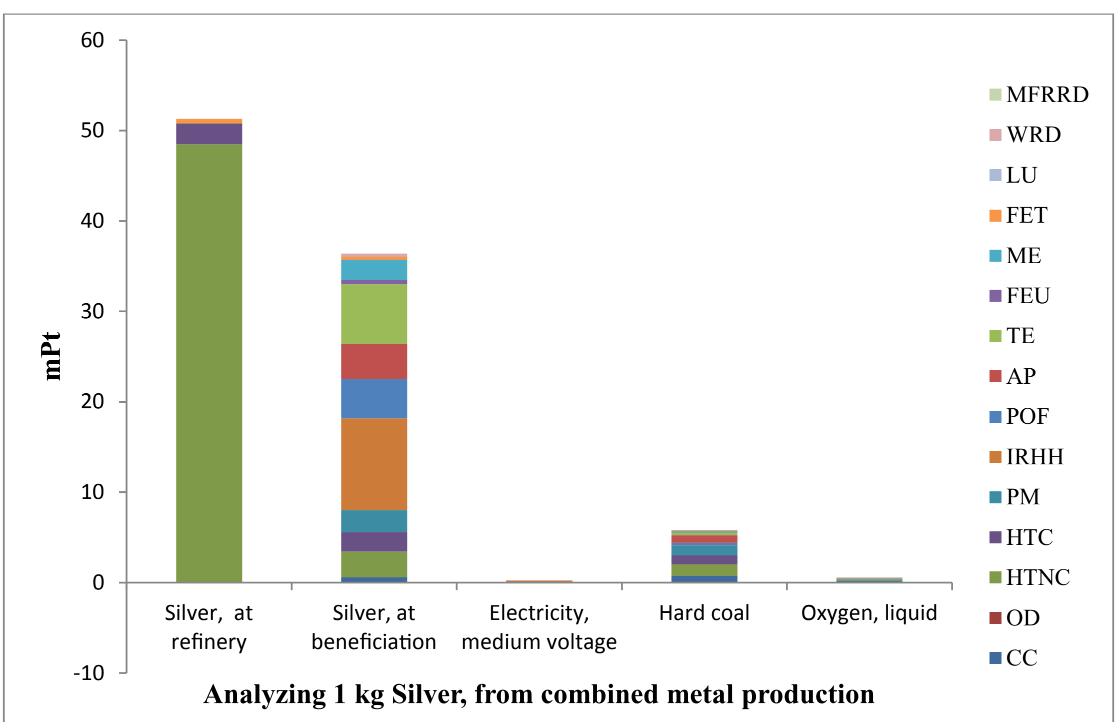

Fig. 10. LCA results for silver refining produced from combined production of gold-silver-lead-zinc-copper (single scored results).

Table 7
Comparative LCA results of gold-silver refining processes based on the ILCD method.

Impact category	Unit	Gold, from couple production of gold-silver	Silver, from couple production of gold-silver	Gold, from combined metal production	Silver, from combined metal production
CC (Climate change)	kg CO_2 eq.	3.4E04	815.44	9.4E03	161.19
OD (Ozone depletion)	kg CFC-11 eq.	2.2E-03	5.31E-05	2.5E-04	4.26E-06
HTNC (Human toxicity, non-cancer effects)	CTUh	1E-03	2.42E-05	7.1E-03	1.12E-04
HTC (Human toxicity, cancer effects)	CTUh	6E-04	1.45E-05	6.05E-05	1.03E-06
PM (Particulate matter)	kg PM2.5 eq.	28.56	0.689	15.61	0.27
IRHH (Ionizing radiation HH)	kBq U235 eq.	47.15	1.14	2.1E03	37.34
IRE (Ionizing radiation E)	CTUe	4.2E-04	1.02E-05	0.02	3.37E-04
POF (Photochemical ozone formation)	kg NMVOC eq.	295.84	7.14	189.19	3.23
AP (Acidification)	molc H+ eq.	280.98	6.79	233.21	3.98
TE (Terrestrial eutrophication)	molc N eq.	1.2E03	29.95	1.01E03	17.28
FEU (Freshwater eutrophication)	kg P eq.	65.45	1.58	2.85	0.05
ME (Marine eutrophication)	kg N eq.	100.14	2.42	64.81	1.11
FET (Freshwater ecotoxicity)	CTUe	1.3E04	330.61	3.1E03	54.03
LU (Land use)	kg C deficit	1.6E04	389.39	3.6E03	62.06
WRD (Water resource depletion)	m^3 water eq.	225.67	5.45	21.19	0.36
MFRRD (Mineral, fossil & ren resource depletion)	kg Sb eq.	1.02E-10	2.45E-12	6.82E-11	1.17E-12

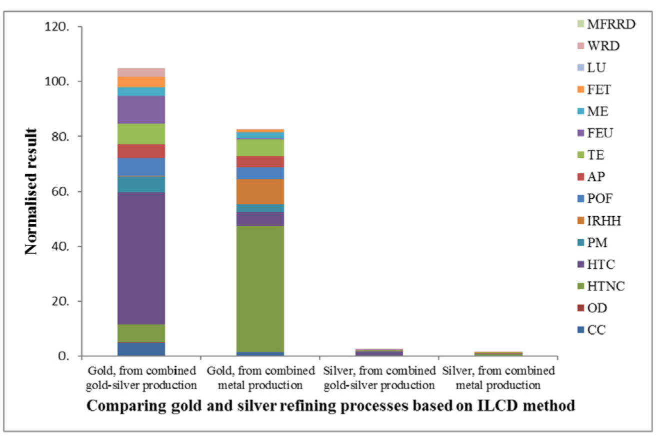

Fig. 11. Comparative LCA results of gold-silver refining processes based on the ILCD method (normalised results).

5.5. Life-cycle inventory emission analysis

Table 11 presents the major life-cycle inventory emissions from the gold-silver refining processes, based on the midpoint indicator-based impact categories analysed from the ILCD method. The results reveal that lead and mercury emission from the gold-refining processes are responsible for human toxicity non-cancer effects while chromium emissions are responsible for human-toxicity cancer effects. For climate change, carbon dioxide biogenic and carbon dioxide fossil are responsible for the highest emissions. Methane, bromotrifluoro-, Halon 1301 emission is responsible for causing ozone depletion. Ammonia and nitrogen oxides affect particulate matter, acidification potential, metal depletion, and terrestrial eutrophication. Carbon and cesium emissions cause ionising radiation effects on human health and ecosystems. Phosphate affects freshwater ecotoxicity. In comparison among the coproduct metals, gold refining emits the largest amount of carbon dioxide, ammonia, nitrogen oxides, and chromium. On the other hand, silver refining from the combined production shows the greatest sustainability of all the processes under consideration.

5.6. Correlation among previous literature and present research

According to the analysis conducted and presented in this paper, it is evident that gold refining is more unsustainable than silver refining. Co-production of other metals also have an impact on the produced precious metal. Though, gold and silver produced from the couple production of gold and silver are responsible for environmental impact rather than for gold and silver produced from the combined production of gold-silver-lead-zinc-copper. The environmental impact categories affected by the gold refining operations are human toxicity (cancer and non-cancer effects), freshwater eutrophication, terrestrial eutrophication, and ionizing radiation (human health). The contributing chemicals responsible for this emission are mercury, lead, chromium, carbon-14, phosphate, ammonia, and nitrogen oxides. According to the previous researches, gold mining is one of the top sources of atmospheric mercury emissions. From the exhaust gas of the converted metal in the refining process, mercury is emitted while the major by-products are waste, cyanide leaching, and sulfuric acid residue (Kahhat et al., 2019; Oraby, 2009; Vitamerry et al., 2017). According to Kahhat et al. more than 80% of the human toxicity is related to the mercury emissions from gold mining. Freshwater ecotoxicity is affected by ore extraction and freighting activities in addition to deforestation. The major impact categories are human toxicity, freshwater ecotoxicity, and climate change in Amazon rainforest (Kahhat et al., 2019). Betancur-Corredor et al. conducted a review study based on environmental effects of gold mining in Columbia that the main environmental effects are due to the pollution of

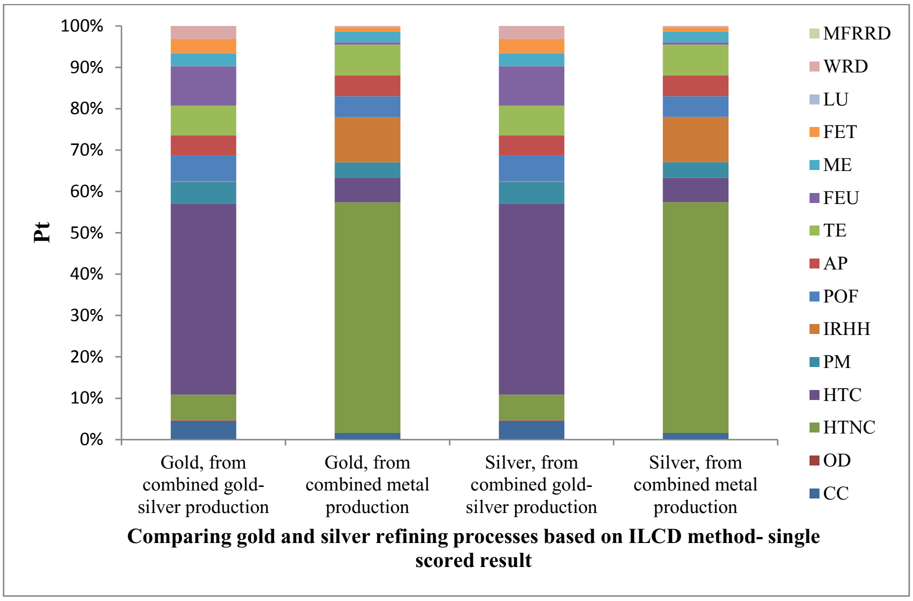

Fig. 12. Comparative LCA results of gold-silver refining processes based on the ILCD method (single scored results).

Table 8
Comparative LCA results of gold-silver refining processes based on the IMPACT 2002 + method (endpoint indicator-based categories).

Damage category	Unit	Gold, couple production	Silver, couple production	Gold, combined production	Silver, combined production
Human health	DALY	0.041	9.9E-04	0.023	3.95E-04
Ecosystem quality	PDF*m^2*yr	3.58E04	866.82	6.68E04	1.14E03
Climate change	kg CO_2 eq.	3.33E04	805.86	9.15E03	156.49
Resources	MJ primary	0.013	3.15E-04	8.76E-03	1.5E-04

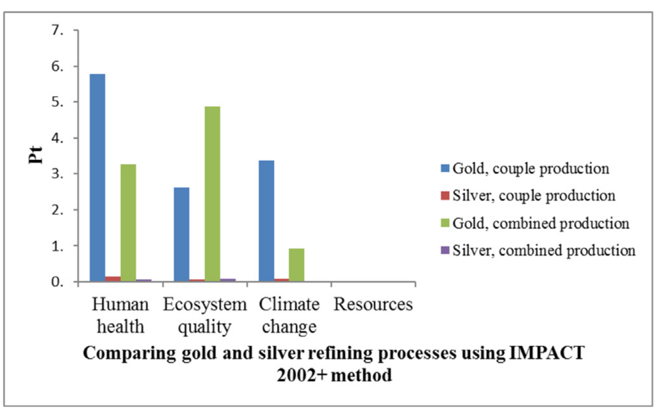

Fig. 13. Comparative LCA results of gold-silver refining processes based on the IMPACT 2002 + method (single score results).

natural ecosystems due to solid waste, mercury emission due to gold amalgamation, and greenhouse gas emissions (Betancur-Corredor et al., 2018). Similar outcomes are found from other researches about the environmental impacts of gold-mining (Chen et al., 2019, 2018; Norgate and Haque, 2012). However, it is evident from the present research that the mercury emission is negligible from the gold refining operation when the gold is produced from the couple production of gold and silver. From the analysis presented in this study, in case of gold-silver couple production, use of chromium steel is mainly accountable for environmental emissions which can be avoided in a small extent after replacing the chromium steel with the low-alloyed or unalloyed steel. In summary, the correlation among this research and the previous studies are strongly linked, while the present research has a notable contribution in identifying the routes of mercury emissions of gold mining, though it is lower than other possible routes of gold mining.

Table 9
Comparative LCA results of gold-silver refining processes based on CED method.

Impact category	Unit	Gold, from couple production of gold-silver	Silver, from couple production of gold-silver	Gold, from combined metal production	Silver, from combined metal production
Renewables	MJ LHV	3.5E03	84.55	1.8E04	315.11
Fossil fuels - oil	MJ LHV	2.4E05	5.7E03	1.4E04	250.04
Fossil fuels - gas	MJ LHV	2.4E05	5.7E03	1.1E04	198.53
Fossil fuels - coal	MJ LHV	2.1E04	514.	6.2E04	1.06E03
Biomass	MJ LHV	3.4E03	81.57	12E04	203.44
Nuclear	MJ LHV	1.4E03	34.17	5.6E04	954.83
Embodied energy LHV	MJ LHV	5.09E05	1.2E05	1.7E05	2.9E03
Embodied energy HHV	MJ HHV	5.3E05	1.3E04	1.7E05	3.04E03

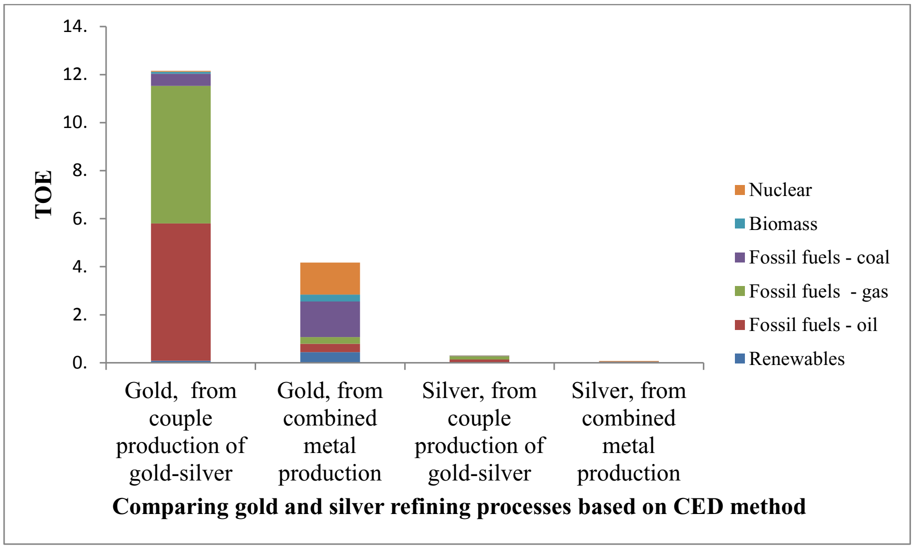

Fig. 14. Comparative LCA results of gold-silver refining processes based on CED method (normalised results).

Table 10
Sensitivity analysis results of gold-silver refining processes based on the ILCD method.

Impact category	Unit	Gold			Silver		
		Case study 1- base case	Case study 2- low alloyed steel	Case study 3- unalloyed steel	Case study 1- base case	Case study 2- low alloyed steel	Case study 3- unalloyed steel
CC (Climate change)	kg CO_2 eq.	3.4E04	3.3E04	3.3E04	815.44	799.35	796.39
OD (Ozone depletion)	kg CFC-11 eq.	2E-03	2.2E-03	2.2E03	5.31E-05	5.29E-05	5.29E-05
HTNC (Human toxicity, non-cancer effects)	CTUh	1E-03	6E-04	5.4E-04	2.42E-05	1.45E-05	1.31E-05
HTC (Human toxicity, cancer effects)	CTUh	6E-04	1.2E-04	5.88E-05	1.45E-05	2.99E-06	1.42E-06
PM (Particulate matter)	kg PM2.5 eq.	28.56	27.39	27.2	0.68	0.66	0.66
IRHH (Ionizing radiation HH)	kBq U235 eq.	47.15	7.03	1.33	1.14	0.17	0.03
IRE (Ionizing radiation E)	CTUe	4.2E-04	6.06E-05	9.15E-06	1.02E-05	1.46E-06	2.21E-07
POF (Photochemical ozone formation)	kg NMVOC eq.	295.84	293.63	293.18	7.14	7.09	7.08
AP (Acidification)	molc H+ eq.	280.98	276.45	275.65	6.78	6.68	6.66
TE (Terrestrial eutrophication)	molc N eq	1.2E03	1.2E03	1.2E03	29.95	29.76	29.72
FEU (Freshwater eutrophication)	kg P eq.	65.45	65.47	65.45	1.58	1.58	1.58
ME (Marine eutrophication)	kg N eq.	100.14	99.43	99.29	2.42	2.4	2.39
FET (Freshwater ecotoxicity)	CTUe	1.3E04	8.2E03	7.5E03	330.61	199.66	181.64
LU (Land use)	kg C deficit	1.6E04	1.6E04	1.6E04	389.39	387.6	386.78
WRD (Water resource depletion)	m^3 water eq.	225.67	224.62	224.43	5.45	5.42	5.42
MFRRD (Mineral, fossil & ren resource depletion)	kg Sb eq.	1.02E-10	9.99E-11	9.83E-11	2.45E-12	2.41E-12	2.37E-12

6. Conclusion

This paper presents the life-cycle assessment of gold-silver refining processes, compares their inputs, outputs, impact categories, and discusses some ways to reduce the environmental impacts of refining processes. The results show that gold refining has higher environmental effects as compared to silver refining. Gold-silver refining processes are mainly responsible for human toxicity (cancer and non-cancer) effects caused by higher emissions of lead and mercury into the environment. Between the two types of refining processes, gold-silver refining from the couple production of gold and silver is detrimental for environmental sustainability. Sensitivity analysis is carried out by replacing the steel consumed in the refining process. Alternative options such as low-alloyed or unalloyed steel instead of the steel chromium 18/8 could reduce the environmental burdens associated with precious metal refining processes for some of the impact categories. However, that needs significant research to check the feasibility of such alternative options. Most of the midpoint based environmental impact categories show better results in the sensitivity analysis except the freshwater ecotoxicity. However, further research should be carried out to reduce steel consumption or to control the lead and mercury emissions from the refining processes.

Table 11
Life-cycle inventory emissions based on impact categories.

Impact category	Substance	Unit	Gold, couple production	Silver, couple production	Gold, combined production	Silver, combined production
CC	Carbon dioxide, fossil	kg CO_2 eq.	1.84E04	443.96	5.67E03	97.092
OD	Methane, bromotrifluoro-, Halon 1301	kg CFC-11 eq.	2.17E-03	5.26E-05	1.34E-04	2.29E-06
HTNC	Lead	CTUh	7.2E-05	1.74E-06	4.07E-03	6.97E-05
	Mercury	CTUh	4.32E-05	1.04E-06	1.41E-03	2.43E-05
HTC	Chromium, air	CTUh	4.9E-04	1.2E-05	3.04E-07	5.19E-09
	Chromium VI, water	CTUh	5.53E-05	1.34E-06	2.43E-05	4.14E-07
PM	Ammonia	kg PM2.5 eq.	0.82	0.02	1.6	0.03
	Nitrogen oxides	kg PM2.5 eq.	1.67	0.04	1.04	0.02
IRHH	Carbon-14	kBq U235 eq.	44.26	1.07	2.06E03	35.18
IRE	Carbon-14	CTUe	3.13E-04	7.57E-06	0.02	2.5E-04
	Cesium-137	CTUe	8.47E-05	2.04E-06	4.02E-03	6.87E-05
POF	Nitrogen oxides	kg NMVOC eq.	231.23	5.58	144.41	2.46
	Nitrogen oxides	kg NMVOC eq.	11.61	0.28	13.24	0.22
AP	Ammonia	molc H+ eq	37.19	0.89	72.47	1.24
	Nitrogen oxides	molc H+ eq	171.11	4.13	106.87	1.83
TE	Ammonia	molc N eq	166.23	4.01	323.96	5.53
	Nitrogen oxides	molc N eq	985.03	23.78	615.19	10.5
FEU	Phosphate	kg P eq.	65.42	1.58	2.82	0.05
ME	Nitrogen oxides	kg N eq.	89.95	2.17	56.18	0.95
	Nitrogen oxides	kg N eq.	4.52	0.11	5.15	0.09
FET	Chromium	CTUe	5.03E03	121.47	3.08	0.053
	Vanadium	CTUe	5.25E03	126.92	553.48	9.46
LU	Occupation, dump site	kg C deficit	5.98E03	144.55	269.01	4.59
	Occupation, forest, extensive	kg C deficit	3.62E03	87.37	2.97E03	50.27
WRD	Water, cooling, unspecified natural origin/m^3	m^3 water eq.	7.99	0.19	6.74	0.11
	Water, river	m^3 water eq.	1.34	0.03	12.44	0.21
MFRRD	Gas, mine, off-gas, process, coal mining/m^3	kg Sb eq.	1.02E-10	2.45E-12	6.82E-11	1.17E-12

Nomenclature

Term Description
kg CO_2 eq Carbon dioxide equivalent
kg CFC-11 eq Ozone Depletion Potential OZDP kg CFC-11 equivalent
CTUh Comparative Toxic Unit for humans
kg PM 2.5eq Unit for particulate matter
kg NMVOC eq non-methane volatile organic compounds equivalent
Molc H+ eq Mole of Hydrogen equivalent
Molc N eq Mole of Nitrogen equivalent
kg P eq Kilograms of Phosphorus equivalent
kg N eq Kilograms of Nitrogen equivalent
CTUe Comparative Toxic Unit for ecosystems
M^3 H_2O Volume of water supply
kg Sb eq kilogram of Antimony equivalent
kg O_3 eq Kilogram of ozone equivalent
DALY Disability adjusted life year
PDF*m^2*yr Potentially Disappeared Fraction of species over a certain area over a certain time
MJ primary Total life cycle primary energy use

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